

## EVALUATION OF METEOROLOGICAL AIRBORNE DOPPLER RADAR

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ABSTRACT

This paper will discuss the capabilities of airborne Doppler radar for atmospheric sciences research. The evaluation is based on airborne and ground-based Doppler radar observations of convective storms. The capability of airborne Doppler radar to measure horizontal and vertical air motions is evaluated. Airborne Doppler radar is shown to be a viable tool for atmospheric sciences research.

## 1. INTRODUCTION

Ground-based Doppler radars have been used since the 1960's to measure air and cloud particle motions in a wide variety of situations. Excellent reviews are given by Atlas (1964), Lhermitte (1966), Doviak et al (1979) and Carbone et al (1980). Multiple Doppler radar techniques have been extensively used to study atmospheric phenomena including convective clouds (e.g. Lhermitte, 1975; Heymsfield et al, 1980; Ray et al, 1981) stratiform clouds (e.g. Heymsfield, 1979) and boundary layer structure (e.g. Kropfli and Hildebrand, 1980). These and other studies have shown ground-based Doppler radars to be valuable instruments for atmospheric sciences research, which enable the measurement of air motions over large volumes in short lengths of time. Ground-based Doppler radar studies are limited to the observation of phenomena which develop within or traverse the area covered by the radars. Many meteorological phenomena cannot be observed adequately by ground-based Doppler radars because of their size or their distance from the radars.

The recent interest in airborne Doppler radar has resulted from the anticipated ability of the airborne Doppler radar to transcend some of the problems inherent with ground-based radars. Early tests of the airborne Doppler radar aboard the NOAA P-3 aircraft (Trotter et al, 1980, 1981) investigated the capabilities of the airborne Doppler system to function in the aircraft environment. These tests indicated that cloud particle velocities measured by the airborne Doppler radar were generally within about 1 m/s of comparable velocities measured simultaneously by a ground-based Doppler radar.

More extensive tests of airborne Doppler radar capabilities have been presented by Jorgensen et al (1983a), Hildebrand et al (1983a) and Mueller and Hildebrand (1983). Jorgensen et al (1983a) presented comparisons of airborne and ground-based Doppler radar measurements of horizontally homogeneous stratiform precipitation. They compared dual Doppler-derived horizontal wind fields from airborne and ground-based Doppler radar systems. Their measurements showed agreement between the airborne and ground-based horizontal vector fields, but a lack of agreement between the vector eddy fields measured by the two systems. This lack of agreement between the airborne and ground-based systems was attributed to the long data collection period, the non-stationarity of the wind field over this period, and to differences in the sampling characteristics of the two systems.

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They also presented a direct comparison of precipitation fall speeds as observed by airborne and ground-based Doppler radars. These measurements indicated that the airborne and ground-based mean Doppler velocity measurements agreed to  $\ll 1$  m/s, but that the variance of the airborne mean fall speed measurements was considerably larger than that measured by the ground-based system (about  $1.4$  vs  $0.25$   $\text{m}^2/\text{s}^2$  for the airborne vs ground Dopplers). The increased variance noted in the airborne data was attributed to variabilities and uncertainties of the order of  $0.3$  degrees in the airborne Doppler antenna position. Jorgensen et al (1983b) and Marks and Houze (1983) presented analyses of convective storm and hurricane structures using the P-3 airborne Doppler data.

Mueller and Hildebrand (1983) and Hildebrand et al (1983a) presented analyses of airborne and ground-based Doppler radar data collected under more optimal conditions.

These analyses are extended in the present paper to include more careful comparisons of vertical and horizontal air motions within convective storms as measured by airborne and ground-based Doppler radars. The strengths and weaknesses of both systems are noted and some comments are made concerning the utility of airborne Doppler radar in measuring atmospheric air motions. Hildebrand et al (1983b) discuss characteristics of airborne Doppler radars, and recommend some conventions which will ease the incorporation of the airborne radar data into multiple Doppler analyses. They also discuss some strategies of operation for airborne Doppler radar.

## 2. DATA COLLECTION

The data used in this paper were collected during the Joint Airport Weather Study (JAWS) experiment during June 1982. During JAWS the NCAR Doppler radars, CP2 and CP4, were located within  $<30$  km of each other near Denver, Colorado as shown in Fig. 1. These radars have about  $1$  degree beams, and contiguous  $150$  m range bins. During JAWS these radars generally scanned in a series of sector scans, with beams separated by less than  $1$  deg in azimuth and elevation. The volume scan time was generally  $< 3$  minutes. The CP2 radar is a dual wavelength X and S-band radar, with the S-band being Doppler. The CP4 is a C-band Doppler radar.

The NOAA P-3 airborne Doppler radar is summarized in Jorgensen et al (1983a) and Hildebrand et al (1983b). The radar is located in the tail of the P-3 aircraft and scans in a vertical plane normal to the ground track. The antenna scans are corrected for the drift and pitch of the aircraft so that the airborne Doppler-measured radial velocities are measured relative to the ground. The aircraft's forward motion translates the beam through space in such a fashion as to produce a helical scan surface with the aircraft track at the center. The aircraft flies about  $1$  km in the time it takes to complete one scan. This X-band radar has a beamwidth of  $1.9$  degree in the cross-track direction and  $1.35$  degree in the along track direction. The scan and sampling rates for the radar are such that one beam of data is collected every degree in the vertical direction. The airborne Doppler radar collects 256 bins of data per beam, with  $75$  m deep bins spaced at  $150$  or  $300$  m intervals. The data used in this paper are at  $150$  m spacing.

## 3. MEASUREMENT OF HORIZONTAL VELOCITIES

On 25 June 1982, the airborne and ground-based Doppler radars observed a thunderstorm which was located about  $40$  km southwest of the ground-based radars. The analysis location and the P-3 flight track are indicated in Fig. 1.

The storm had a maximum reflectivity of about 55 dBZ and was moving towards the northeast at about 10 m/s. These data are well suited for evaluating the capabilities of the airborne Doppler radar to measure horizontal velocities within storms.

The ground radars scanned the storm several times at 2-3 minute intervals. At the same time, the airborne Doppler collected data while flying at a distance of 15-25 km from the storm. The P-3 data were collected over a 7 minute period which was centered upon the time when the ground-based radars were collecting data. In order to correct for errors in the P-3 position, the aircraft position was adjusted such that the interpolated radar reflectivity fields from the aircraft and ground radars matched in location. This involved adjustments to the P-3 position of 1-2 km in the south and west directions. (Subsequent to the preliminary results presented herein, an improved adjustment has been developed. This new adjustment differs from the one used in the data presented here by about 1 km.)

The data from the two airborne Doppler flight tracks and from the ground-based Doppler radars were interpolated to a common cartesian grid having dimensions 1 x 1 x 0.6 km in the X, Y, and Z directions. The inverse square interpolation filter had the same scale. During the interpolation, each beam was advected according to the assumed advection velocity of the storm, and the time of data collection of that beam of radar data.

With four radars available for a multiple analysis (CP2, CP4 and the P-3 from two vantage points), several different analyses were generated. Only three will be presented here. These three, shown in Fig. 2, include the airborne only analysis (upper right), the ground based only analysis (lower left)

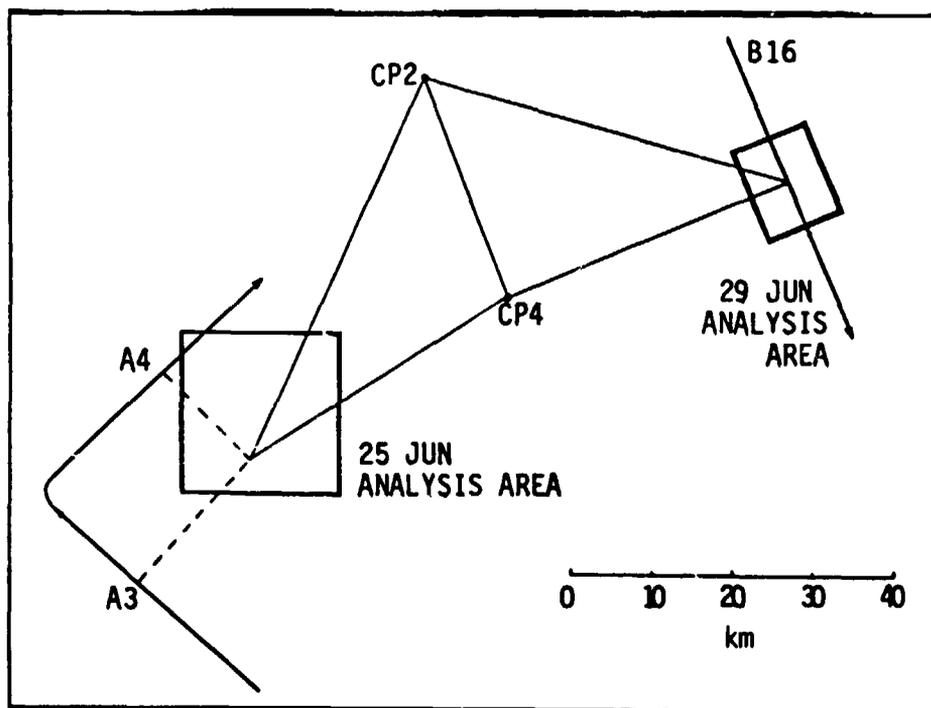
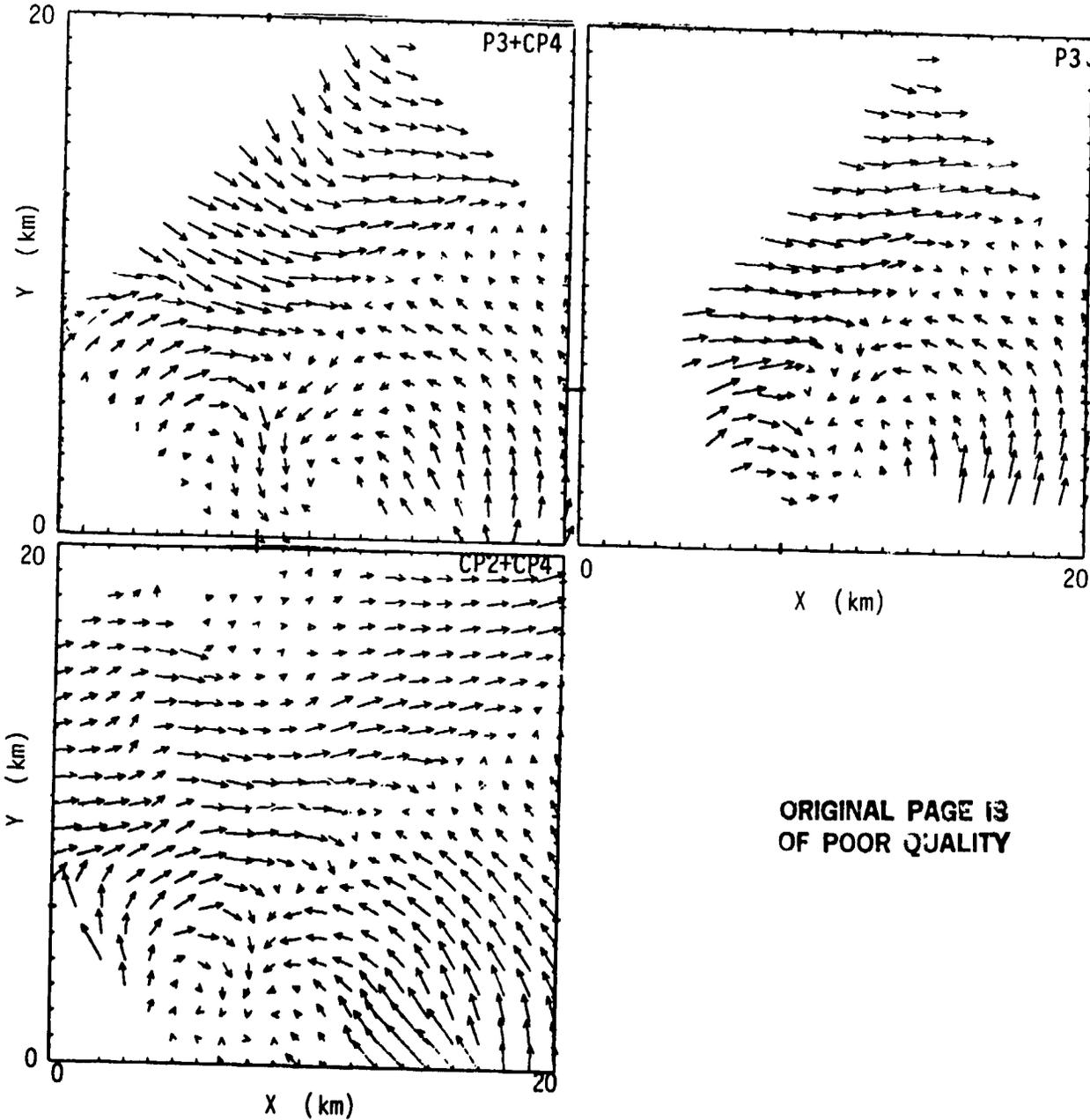


Figure 1. Map showing the location of the ground-based Doppler radars during the JAWS experiment. Also shown are the multiple Doppler radar analysis areas on the two days of the experiment, 25 and 29 June 1982. The flight tracks from 25 June ( A3 and A4 ) and from 29 June ( B16 ) are also shown.

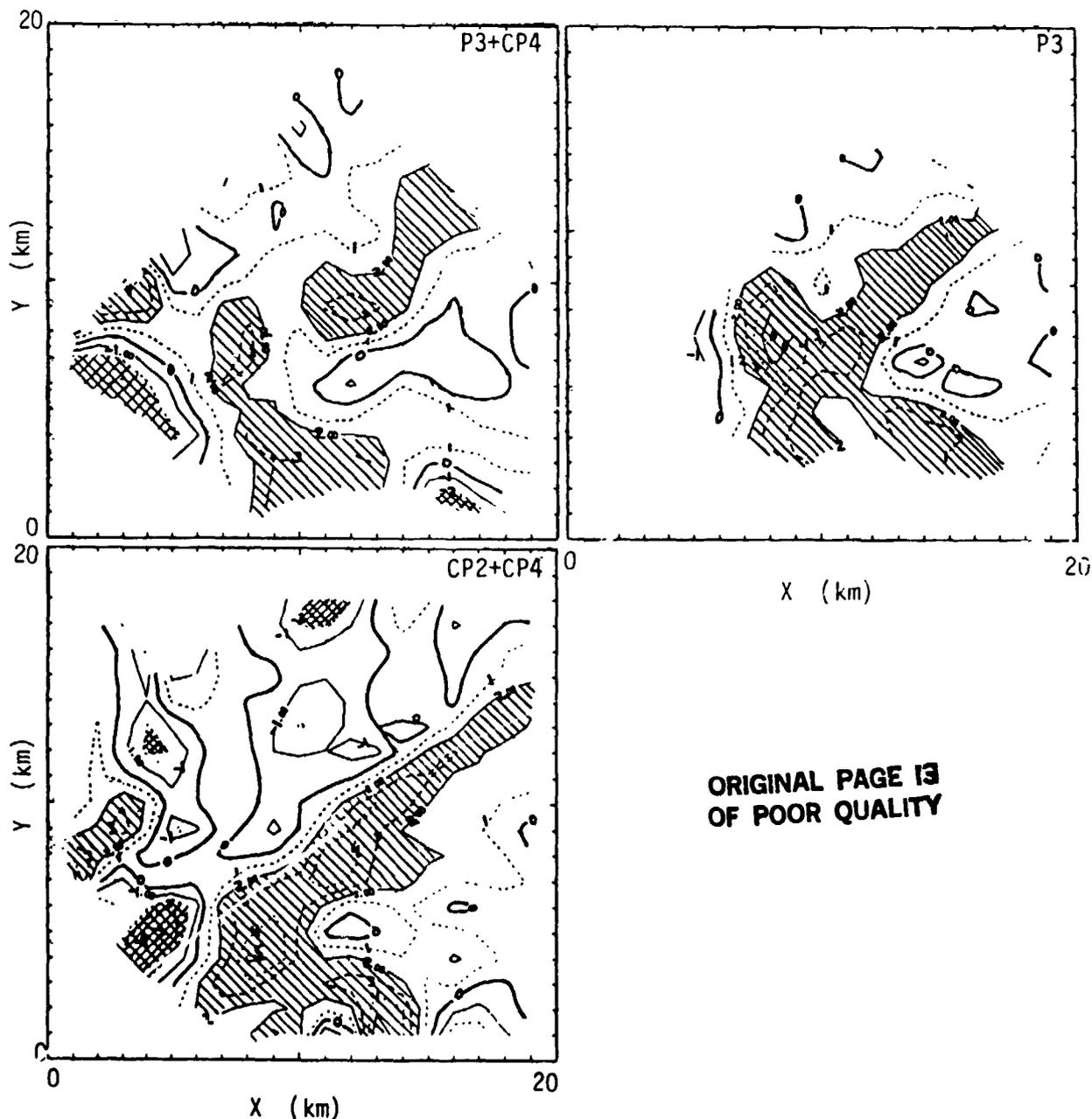
and a combined analysis (upper left) which made use of the second P-3 flight track (A4) and the CP4 radar. Additional analyses which made use of the P-3 + CP2 or the P-3 + CP2 + CP4 were little different from the P-3 + CP4 analysis (upper left). Inspection of the three vector fields in Fig. 2 indicates striking similarities. All three horizontal vector fields (taken from 4.0 km msl or 2.4 km agl) show a convergence line running diagonally up to the right through the data, and the southward outflow on the south side of the storm. The results shown here are indicative of those observed at other levels in the storm.



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Figure 2. Horizontal wind vector fields at the 2.4 km agl level for three different multiple Doppler analyses. The upper left analysis uses airborne Doppler data from flight track A4 plus the CP4 ground based radar. The upper right analysis uses airborne Doppler from flight tracks A3 and A4. The lower left analysis uses data from ground-based CP2 and CP4 radars. A 10 m/s wind vector is 1 km long.

A more stringent test of the analyses lies in comparison of the convergence fields. Fig. 3 shows three convergence fields which correspond to the vector fields of Fig. 2. Areas of convergence of greater than  $2 \times 10^{-3} \text{ s}^{-1}$  are hatched; areas of less than  $-2 \times 10^{-3} \text{ s}^{-1}$  are cross-hatched. These analyses indicate that while the different analyses depicted similar convergence fields, some differences are also noted. All three analyses note the area of convergence noted in Fig. 2. The airborne-only and the ground based-only analyses (upper right and lower left) also indicate similar convergence maxima of  $5 - 6 \times 10^{-3} \text{ s}^{-1}$ ; however, the position they indicate for the maximum is somewhat different. This difference is, in part, due to the error in aircraft location.



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Figure 3. Horizontal convergence fields corresponding to the vector fields of Fig. 2. The contours are in units of  $10^{-3} \text{ s}^{-1}$ . Areas with convergence greater than  $2 \times 10^{-3} \text{ s}^{-1}$  are hatched; areas less than  $-2 \times 10^{-3} \text{ s}^{-1}$  are cross-hatched.

An additional means of comparing the quality of the analyses lies in resampling the three-dimensional wind fields. For each analysis in Fig. 2 a radial velocity field was generated which corresponded to what the CP2 radar would see if it looked at this analysis. This "resampled" radial velocity was then subtracted from what the CP2 radar actually saw. This difference is displayed in Fig. 4. On the left side of the figure is the CP2 radial velocity difference for the P-3 + CP4 analysis. On the right side of the figure is the CP2 radial velocity difference for the airborne-only analysis (P-3 tracks A3 and A4). In both cases, differences greater than +2 m/s are shaded. The airborne-only analysis agrees to better than 2 m/s except in the core of the storm near the updraft. Two possible causes of error include the approximately 1 km error in aircraft location and the relatively long time required to collect the airborne Doppler data (about 7 minutes). Both effects could degrade the wind measurements, particularly in areas of high temporal and spatial gradients such as near the edge of an updraft or downdraft.

The areas of large error for the P-3 + CP4 analysis (left portion of Fig. 4) tend to be concentrated to the sides, away from the convergence area. The reason for this error pattern is not clear. Based on the radar locations (Fig. 1.), it appears the poorest geometry should occur toward the north edge of the analysis area. While the effects of the 1 km aircraft location error certainly enter this comparison, these explanations shed little light on the results shown in Fig. 4. Similar figures which contain data from CP2 are not shown for, as expected, they contain only numbers smaller than about 1 m/s.

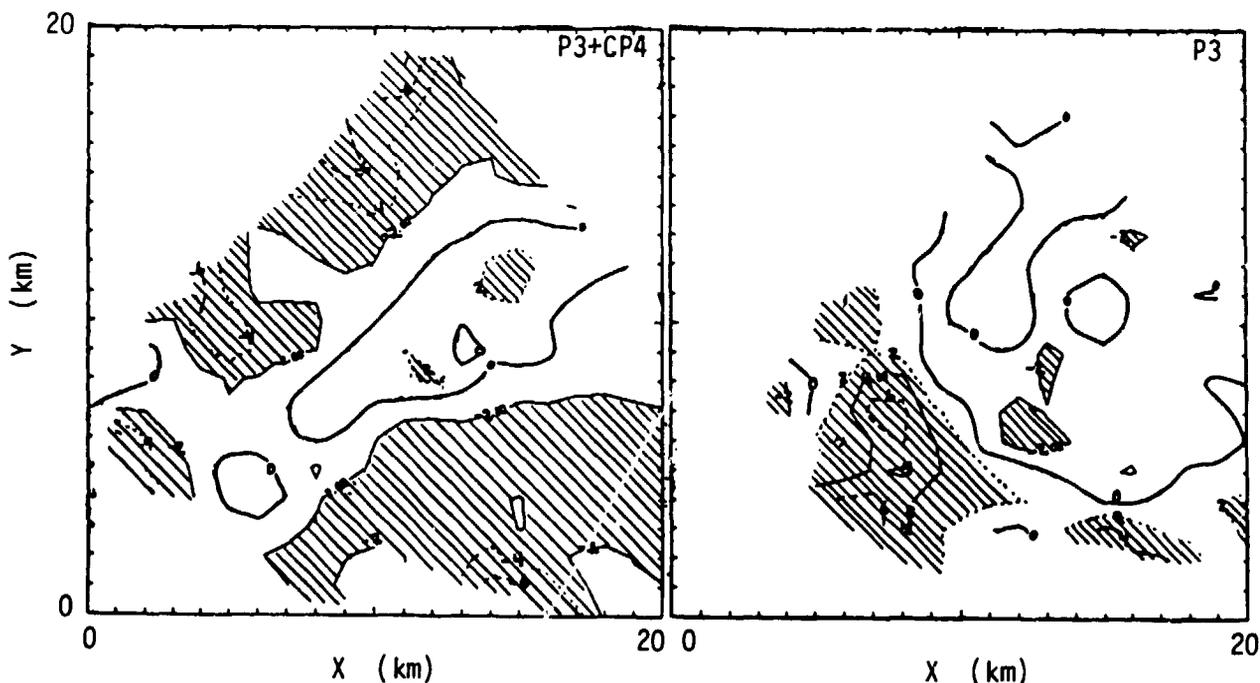


Figure 4. The difference between the observed CP2 radial velocities and resampled radial velocities taken from the top two analyses of Fig. 2. The resampled radial velocities are what the CP2 radar would see were it to observe the wind fields depicted in the upper portion of Fig. 2. The contours are in units of 1 m/s. Areas of  $> 2$  m/s or  $< -2$  m/s are hatched.

#### 4. MEASUREMENT OF VERTICAL VELOCITIES

On 29 June 1982 the P-3 aircraft flew directly through a microburst-producing thunderstorm at an altitude of 4.5 km agl. The aircraft made repeated passes through the storm until the severity of the storm became too great for further penetration. During this time the storm was observed by the ground-based CP2 and CP4 radars. Due to the location of the airborne Doppler immediately above the microbursts, this case provides a good evaluation of the airborne Doppler radar's ability to measure vertical storm velocities, while operating in conjunction with ground-based Doppler radars. This test is one of the primary areas of interest expressed in the 1979 Multiple Doppler Radar Workshop (Carbone et al, 1980).

In this case the airborne Doppler was operated as described above. The ground-based Doppler radars scanned with a volume scan time of about 2.5 minutes. At the center of the analysis volume (Fig. 1) the horizontal data density was 0.3 km and the vertical data density was 0.25 km. The data from the airborne and ground-based radars were interpolated to a cartesian grid which was rotated such that the Y axis was parallel to the aircraft flight track. For the airborne Doppler radar data the grid resolution and interpolation filter length was 0.35 x 1.05 x 0.25 km in the X, Y and Z directions. The ground-based Doppler data were interpolated on a similar grid which had a 0.35 grid spacing and filter length in the Y direction. Otherwise the analyses were identical. The difference in the airborne and ground-based analyses was selected because of the ~1 km data spacing of the airborne Doppler data in the Y direction. Due to this wide data spacing and the strong distance weighting, the interpolated airborne data are not well smoothed in the Y direction. This problem was exacerbated by having the grid nearly coincide with the airborne Doppler data collection locations in the Y direction. The ground-based Doppler data, on the other hand, are much denser in the Y direction. When interpolated using an identical filter and grid, the ground-based data are smoother than the airborne Doppler data. Due to the small scale of the observed microburst a higher resolution ground-based Doppler analysis was necessary in order that the results be as closely comparable as possible.

Some sample data are presented in Fig. 5. The horizontal wind vector field at the top of the figure is ground radar data from 0.1 km agl. Vertical cross-sections at the bottom of Fig. 5 show the X-Z wind vectors in the Y=3.5 km and Y=11 km planes. For each plane, two analyses are shown. The top analysis is a ground-based (CP2 + CP4) analysis in which the vertical velocity vectors were derived using continuity and the assumption of zero vertical velocity at the ground. The lower analysis is derived using the airborne Doppler data for derivation of the vertical velocity. The airborne radial velocity values are corrected for the horizontal velocities observed by the ground-based radars and for a hydrometeor fall speed which was based on the observed radar reflectivity value. The residual radial component was attributed to the vertical velocity. Both vertical velocity contours and X-Z wind vectors are presented. The radar reflectivity fields are shown as the background contours, behind the U-W wind vectors in the lower section of the figure.

In the left hand column (Y=3.5 km) the different vertical velocities agree well in the center of the figure, where both analyses show a downdraft peak of >12 m/s. To the left of that downdraft, both analyses show a second downdraft; however, the two analyses are somewhat different. The ground-based analysis shows an updraft at about X=2.5 km then another downdraft area between X=0.5 and X=1.5 km. In contrast, the airborne Doppler shows a uniform area of downdraft on the left side of the figure. The airborne Doppler evaluation of

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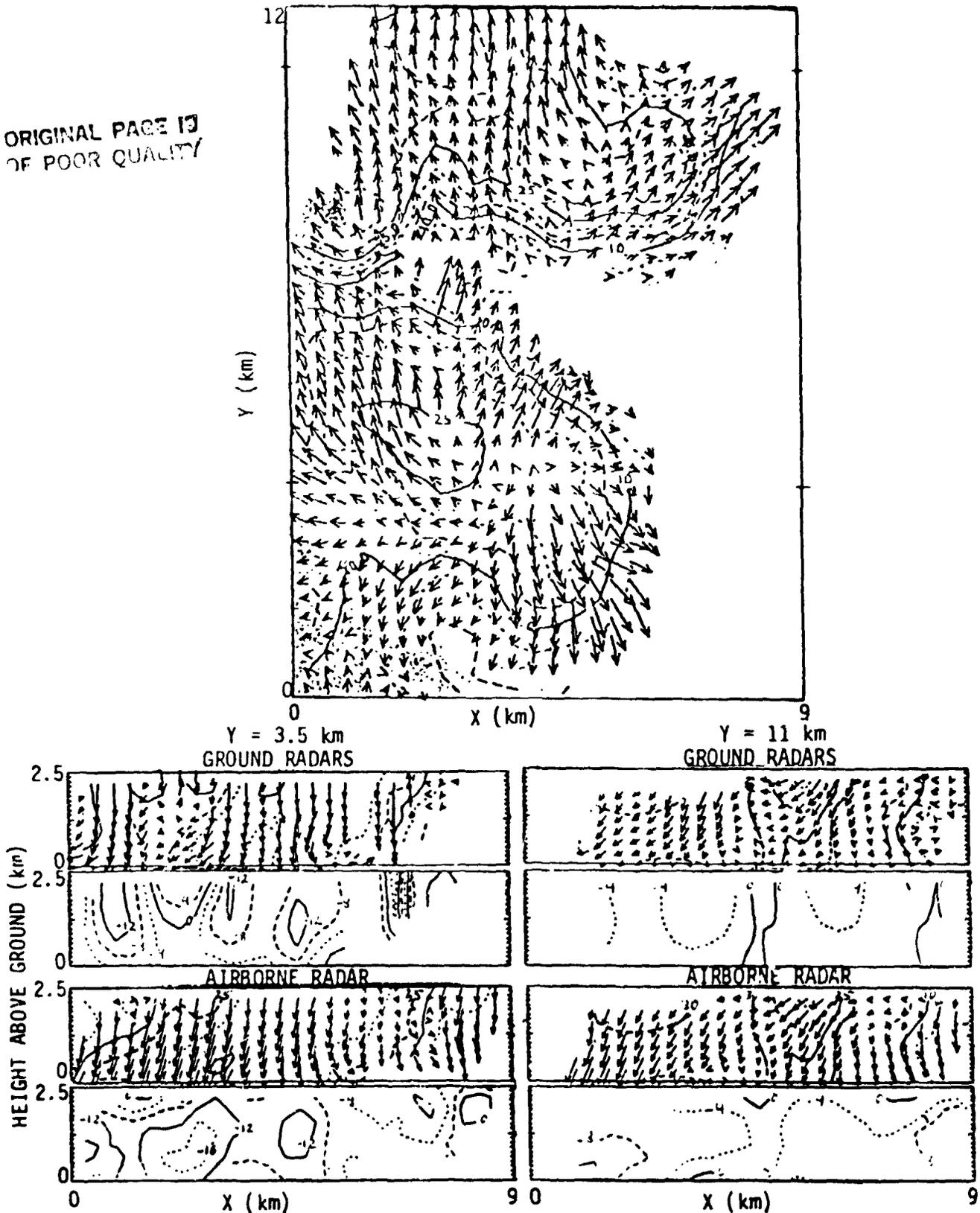


Figure 5. Vertical velocity analyses based on airborne and ground-based Doppler radars. The upper portion of the figure is a horizontal wind vector field at the 0.1 km agl level, based on the ground radars. The lower left portion shows vertical cross-sections located at  $Y=3.5$  km for the airborne and ground-based analyses. Both the U-W vector fields and the W contours are shown. The lower right portion is a similar vertical cross-section located at  $Y=11$  km. The reflectivity is shown as background to the airborne Doppler D-W wind fields.

the vertical velocities seems in better agreement with the reflectivity profile which is shown in the next to bottom frame of the figure. The analysis in the upper frame shows fairly strong  $dV/dY$  in that area which could be mis-estimated due to the poor geometry of the ground Doppler radars for making velocity measurements in the Y direction.

Agreement is also seen in the  $Y=11$  km vertical planes in the lower right of Fig. 5. There, both analyses present a minimum in vertical velocity at about  $X=4.5$  km, and both analyses show downdrafts of about 4 m/s through much of the rest of the  $Y=11$  plane. The major difference between these two analyses lies at the edges of the plane near  $X=1$  and  $X=8$ , where the airborne analysis (lower) shows intensified downdrafts and the ground based analysis (upper) shows weakened downdrafts. There appears as much reason to question the ground based horizontal divergence fields as there is to question the airborne radial velocity fields.

## 5. DISCUSSION

These comparisons of airborne and ground-based Doppler radar data are encouraging. Although the results must be regarded as preliminary at this point, they indicate that the airborne Doppler data generally are in qualitative agreement with the ground-based Doppler data. Examples have been presented which use the airborne Doppler primarily to measure horizontal velocities. This mode of use of airborne Doppler radar was recognized in the Multiple Doppler workshop and is of interest for the GALE and STORM experiments. Our analyses indicate areas in which the airborne Doppler is measuring the same things as the ground-based Dopplers, and areas where differences are observed. Generally these differences are small with respect to the total natural velocity differences; however, they are not negligible. The comparison of vertical velocities from the airborne and ground-based Doppler radars produced similar results. Again, there was general qualitative agreement between the two analyses and areas of good and poor agreement in different locations in the analysis. Current extensions of the preliminary results presented here suggest that several effects may be contributing to the observed differences. These effects include the temporal evolution and the advection problems mentioned above, as well as ground clutter and side lobe effects which can be inferred to exist in the data. In addition, there are indications that analysis decisions such as grid spacing and filter shape, as well as radar location, may have significant effects on the analysis. These effects are currently being investigated.

These analyses are currently being extended to include additional cases which include different geometries and an additional radar. Planned extensions of the work include evaluation of multiple Doppler radar analysis decisions on the analysis results as applied to this problem. If available, corroborating aircraft and surface mesonet information will be used for independent verification of analysis results. The implications of the present finding for the design of field projects using airborne Doppler radar is being considered.

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